APPLICATION OF GEOMORPHIC PRINCIPLES TO ENVIRONMENTAL MANAGEMENT IN SEMIARID REGIONS

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February 1980

Completion Report No. 93

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OWRT Project No. B-150-COLO

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Submitted to

Office of Water Research and Technology
U.S. Department of the Interior
Washington, D. C. 20240

February, 1980

The work upon which this report is based was supported (in part) by funds provided by the U. S. Department of the Interior, Office of Water Research and Technology, as authorized by the Water Resources Research Act of 1978, and pursuant to Grant Agreement No. 14-34-0001-7143.

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ABSTRACT

The incision of gullies into valley alluvium is a severe soil conservation problem, resulting in deterioration of agricultural land, sediment pollution, filling of reservoirs, and water table lowering in the valley floor. Therefore, it is of importance to identify as accurately as possible those valleys which are prone to gullying, in order to establish priorities for soil conservation treatment within a geomorphically similar area. In other words, what is needed is an operational definition of the geomorphic threshold above which gully incision into the valley alluvium occurs.

In many valleys of the semiarid west valley floors are either flat and vegetated without a channel, or they are gullied. It will be of value to establish under what conditions the stable valley floor is incised by discontinuous gullies. Normally the explanation is a large storm, overgrazing or other man-induced changes; however, the character of the valley floor also plays an important role. The valley floor itself can provide a means of recognizing incipiently unstable conditions that lead to incision.

Using previously collected data from the Piceance Creek area of western Colorado, it is possible to identify a valley-slope threshold above which, for a given drainage area, gullying is certain. Below this valley-slope threshold the valley floors are stable; above it they are susceptible to gullying.

When the relations and techniques developed in western Colorado were applied to a similar situation in northeastern Colorado, the Chalk Bluffs area, it was determined that valley width was also a significant factor determining valley stability, and a ratio of valley slope to valley width could be used to identify at a given drainage area a threshold zone of valley floor instability.

These relations explain the observed variability of gullies and also permit identification of those locations where gullying is probable.

ACKNOWLEDGEMENTS

This study was funded in part by a grant from the U.S. Office of Water Research and Technology (OWRT) project No. B-150-COLO. Matching funds were provided by Colorado Agricultural Experiment Station, project 151.

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CHAPTER 1

INTRODUCTION

Geomorphologists recognize that the interface between the atmosphere and the solid earth, the landscape, is dynamic. Drainage basins and their components, slopes and channels, are either adjusting rapidly to altered conditions (instability) or they are in dynamic equilibrium with present conditions. Billions of dollars have been spent during the past century to insure that the landscape and its components are in a condition most favorable for man's activities. Major flood control and navigation improvement projects have been largely successful because hydrologic data and hydraulic and engineering principles could be applied to each situation. Elsewhere and on a smaller scale the results have not been as rewarding because the geomorphologic character of the landscape was important but it was ignored.

The following brief statements contain the essence of a geomorphic approach to land management and erosion control:

1) The land surface is complex, dynamic, and it changes with time.

2) The land surface may respond dramatically over a short time both to man-induced changes or to the exceeding of a geomorphic threshold due to natural causes (Schumm, 1973, 1977).

3) The response of a complex landform, for example a drainage basin, to change is itself complex. That is, secondary responses will complicate the adjustment of the system to change (Schumm, 1973, 1977).

The first statement requires little elaboration. A landscape is composed of slopes, divides, channels and floodplains all responding differently to changed environmental conditions. In addition, there is a progressive erosional evolution of a landscape through time. The manner of change, however, depends on geology, climate, vegetation and, of course, land use.

The second statement relates not only to dramatic erosional events that can be directly related to destruction of vegetation, overgrazing, etc. but also to the random occurrence of slope failure and channel trenching (arroyos, gullies) in response to storm events and land use. That is, within an area of otherwise similar conditions erosion occurs in a seemingly random fashion. The explanation may be that a geomorphic threshold has been locally exceeded.

In the oil shale region of northwestern Colorado some valleys are stable and well vegetated whereas others are gullied and eroding. The inverse relation between critical valley slope and drainage area (an index of hydrology) shows that for a given drainage area there is a critical valley slope above which erosion occurs (Fig. 1). This relation breaks down for very small basins less than about 7 square miles in area; probably because of the influence of aspect and the influence on vegetational cover. The valleys that plot above the threshold line are apparently incipiently unstable and liable to failure (erosion). To understand this relation it is necessary to appreciate how erosion progresses in semiarid regions. Sediment delivered to the valleys tend to be stored there progressively steepening the slope of the valley floor. This continues until flushing of the sediment takes place by gullying at a threshold or critical slope. When the gullies heal the process begins again (Schumm and Hadley, 1956; Schumm, 1973). This obviously is a long-term process, and all of a region will not be in the same stage of development. Therefore, during a major flood event or due to overgrazing, only some valleys will trench. By developing a relation

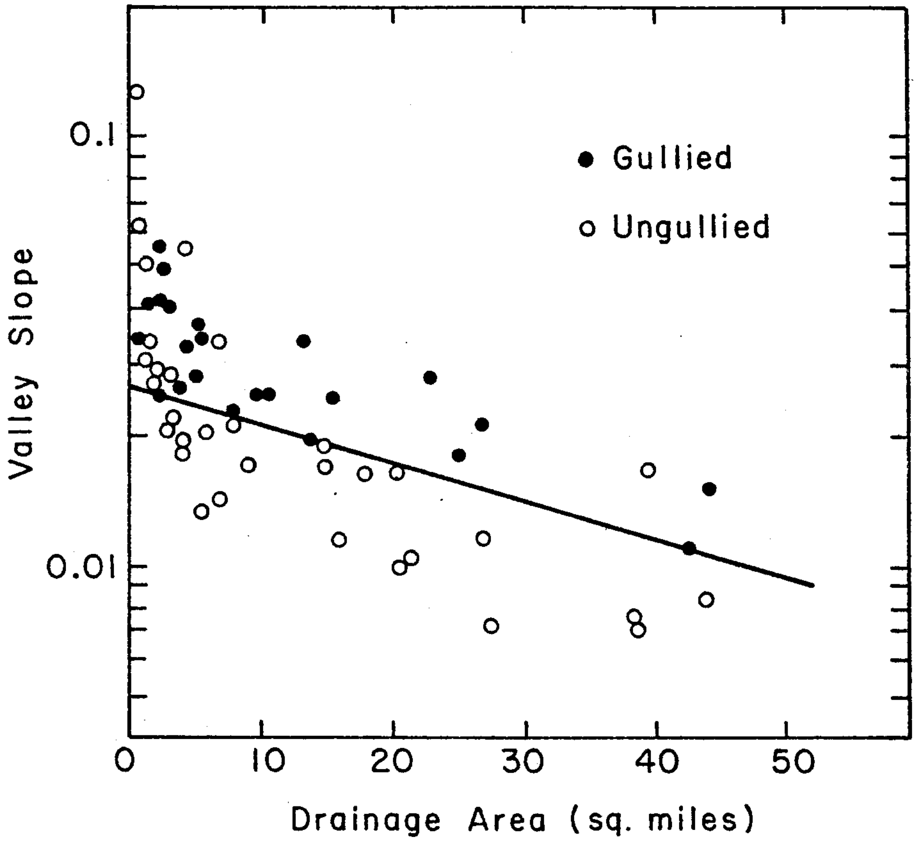

Figure 1 Relation between critical valley-floor slope and drainage area for small drainage basins, Piceance Creek area, western Colorado (from Patton and Schumm, 1975).

such as Fig. 1 for other regions, it may be possible to identify incipiently unstable valleys (those plotting near or above the line, Fig. 1) and to take steps aimed at preventive conservation.

The third statement is based on available field and experimental data that show how a channel or drainage network responds to change by a series of adjustments that leads to a new equilibrium condition. This is referred to as complex response (Schumm, 1977).

In addition, under major changes of base level or climate change the response may be episodic with periods of erosion being separated by periods of deposition (Schumm, 1977).

The research reported herein relates to the second statement and it is an attempt to test and extend the relation shown on Fig. 1. The objective was to develop a procedure for the recognition of incipiently unstable valley floors in semiarid region.

The investigation is focused on the development of discontinuous gullies because they are the first indication of valley instability and they are a harbinger of even greater erosion.

As a first step additional analysis of the Piceance Creek relation was made by Z. B. Begin (Begin and Schumm, 1979). In addition, a field study of the Chalk Bluffs area of northeastern Colorado was undertaken to test the threshold concept in a geomorphically different area (Bradley, 1979).

CHAPTER 2

STABILITY OF VALLEY FLOORS, PICEANCE CREEK AREA

Patton and Schumm (1975) used two simple geomorphic attributes, drainage area and valley slope, to define a discriminant function distinguishing between gullied and ungullied valleys. The data were plotted on a semilogarithmic paper on which the discriminant function is a straight line (Fig. 1). The line represents a relationship of the type:

$$a^A e^S = K$$

where A is drainage area, S is valley slope, e is the base of natural logarithms, and a is a constant. Here, K should be a certain threshold parameter, its value being constant along the discriminant line. However, such a parameter does not bear a clear relation to hydraulic variables such as shear stress or stream power, and the distance of point from that line is but a qualitative measure of valley instability.

Brice (1966) also used drainage area and valley slope in an attempt to define unstable valley floors, plotting these values on log-log paper. He used the regression line of all his data points as the discriminant function, and found that "the ratio of slope to drainage area that is associated with the initiation and rapid growth of a gully is not sharply defined."

Before proceeding, it is necessary to make very clear how the variables of Fig. 1 were obtained. In order to determine what is the critical or threshold valley slope in these alluvial valleys, the gradient of the steepest reach of the valley floor was measured. In these valleys the flat appearing alluvial floors are irregular in a downstream direction, that is there are convex reaches where sediment is stored (Fig. 2). These reaches frequently occur at or downstream from

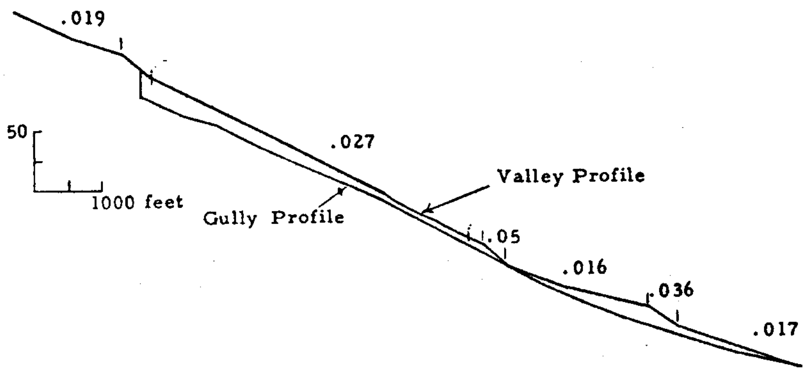

Figure 2 Longitudinal profile of Greasewood Creek, western Colorado. Note irregular valley-floor profile and discontinuous gullies cut below valley floor. Numbers above profile indicate slope of valley floor (from Patton, 1973).

tributary junctions, and within one valley there may be numerous such convexities. The downstream nose of the convexity, which may resemble an in-valley alluvial fan, is the steepest reach of the valley floor and this is the gradient that is measured. The drainage area above this reach is measured, and these two values provide one data point on Fig. 1.

The semiarid valleys of one area frequently are in various stages of stability, gullying, and healing of gullies, and by a study of each of these valley reaches a quantitative assessment of valley stability can be obtained.

The following is a reanalysis of the work of Patton and Schumm (1975). The data collected by Patton (1973) consist of measurements of valley slope and drainage area in 56 valleys. In 23 valleys either continuous or discontinuous gullies were observed, whereas 33 were stable or ungullied. All the valleys are within the semiarid Piceance Creek basin in northwestern Colorado, and the land use, geologic, climatic and gemorphic conditions are very similar throughout the study area (Patton, 1973). Within each valley Patton (1973) identified those reaches which were gullied, or in the absence of gullies, the reach with steepest longitudinal slope. He surveyed the longitudinal slopes of these reaches and measured the drainage areas above these reaches from topographic maps at a scale at 1:50,000. These data, together with Nebraska data published by Brice (1966, Figs. 2 and 3) serve as a basis for discussion.

The approach taken is essentially deductive, starting with a search for a possible threshold parameter, related to gully incision, which has a physical meaning. A reasonable choice is the average shear stress exerted by a flow on the valley floor (Partheniades and Paaswell, 1970; Graf, 1978). This average shear stress is a function of the hydraulic radius of the flow (R), the energy slope (S_e) and the weight per unit volume of the water (γ). All are related by the well-known equation:

$$\tau_o = \gamma R S_e \tag{1}$$

For wide (shallow) flows, R can be replaced by the flow depth (d), and if the energy slope S_e is approximated by the average valley slope S, equation (1) becomes:

$$\tau_o = \gamma d S \tag{2}$$

The problem now is to relate flow depth to the drainage area of the valley.

Using empirical relationships between flow depth (d) and water discharge Q, and similar relationships between water discharge (of an event with a recurrence period of n years, Q_n) and drainage area A (Leopold et al., 1964, pp. 215, 251 and Table 7-5)

$$d = c_1 Q^f \qquad (0.36 < f < 0.45) \tag{3}$$

$$Q_n = c_2 A^r \qquad (0.65 < r < 0.80) \tag{4}$$

c_1 and c_2 are constants. Substituting equation (4) into equation (3):

$$d_n = c_1 c_2{}^f A^{rf} = cA^{rf} \qquad \text{(where } c \text{ is a constant)} \tag{5}$$

From the known range of the exponents f and r, their product rf is expected to be within the range:

$$0.23 < rf < 0.36 \qquad \text{or, say:} \quad 0.2 < rf < 0.4$$

Substituting equation (5) into equation (2), we may define a relationship between average shear stress, drainage area and valley slope. Since this relation is based on simplistic assumptions, a different term is preferred for shear stress which will be denoted here as the shear-stress-indicator (T_o). $T_{o(n)}$ then is only an estimator of the actual shear stress $\tau_{o(n)}$, expected for a storm with a recurrence period of n years, and it is represented by:

$$T_{o(n)} = (c\gamma)A^{rf}S \qquad (6)$$

According to this equation, a line of equal values of the shear-stress-indicator plots as a straight line on a log-log paper. If valley slope S is plotted on the ordinate and drainage area on the abscissa, then the slope of such a line is equal to (-rf).

Patton's data were replotted on a log-log paper with slope on the ordinate (Fig. 3). Following the reasoning of Patton and Schumm (1975), a straight line was drawn through the "lower-most" points of the gullied valleys. This line is assumed to represent the threshold value T_{th} of the shear-stress-indicator, below which valley floors are stable. On Fig. 3 the slope of the line is -0.26, so that $rf = 0.26$, which is within the limits deduced above for the rf exponent.

After the rf exponent was established from the data, equation (6) was used to calculate the values of $A^{0.26}S$, which is equal to $\frac{1}{c\gamma} T_o$, for all the data points. The lowermost value of $\frac{1}{c\gamma} T_o$ for those valleys which are gullied, was considered to represent the threshold value $\frac{1}{c\gamma} T_{th}$.

Then, for each data-point, the value of T_o/T_{th} was calculated thereby eliminating $c\gamma$. This parameter is designated as the relative shear-stress-indicator. Lines of equal T_o/T_{th} values are plotted on Fig. 4 parallel to the basic line $T_o/T_{th} = 1.0$ which is the original line defined as T_{th}.

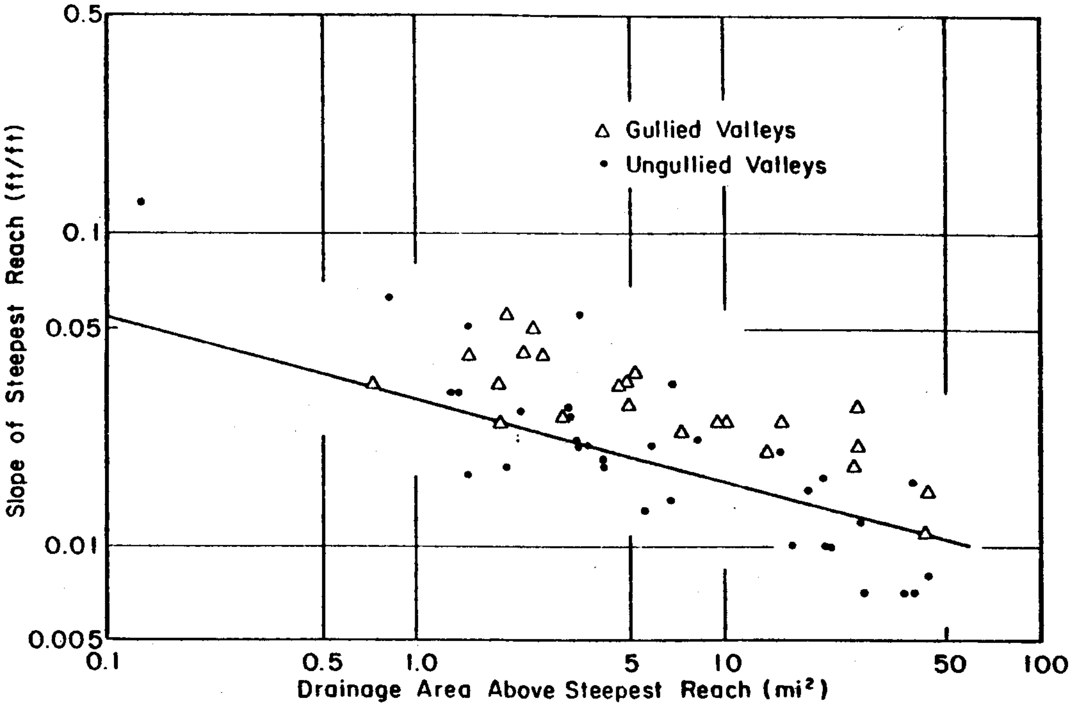

Figure 3 Plot of data from Fig. 1 on logarithmic scales.

Figure 4 shows that, although there are no gullied valleys in the area below $T_o/T_{th} = 1.0$ by definition, there are several ungullied valleys with T_o/T_{th} greater than 1.0. It is, of course, these reaches of valley floors that are potentially the most likely to be eroded in the future and from a land management point of view they are of high priority.

Examination of Fig. 4 reveals that the ungullied valleys with small drainage areas tend to withstand higher values of the relative shear-stress-indicator. This becomes clear by plotting Fig. 5 on which only ungullied valleys were plotted and Brice's (1966) data. The T_o/T_{th} values are insensitive to change in drainage area for areas greater than about seven square miles. However, valleys with smaller drainage areas "survived" markedly increased values of T_o/T_{th}. A related observation was made by Patton and Schumm (1975) who pointed out that their discriminant function is not applicable to basins with small drainage areas. They explained this by suggesting that in small basins the aspect of the valley becomes a dominant factor. Other reasons mya be differences in vegetation cover or shallowness of the alluvial mantle on small, first order streams.

Summary

Although the sample used in this study is small, the results are encouraging.

The method enables a planner to develop rational priorities of soil conservation measures based on an estimated probability of valley incision. However, the above numerical results pertain only to drainage basins with uniform geomorphic and hydrologic characteristics. Different values of the threshold shear-stress-indicator are expected where geology, soils, climate and vegetation are different.

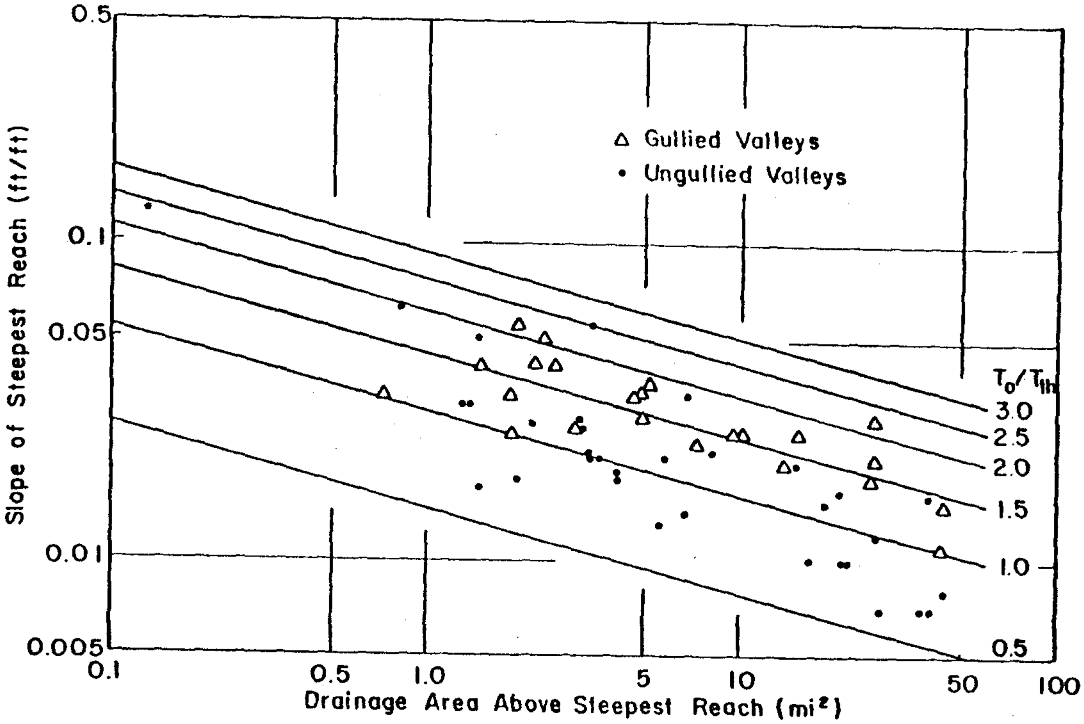

Figure 4 Plot of data from Fig. 1 showing values of Relative Shear Stress Indicator (from Begin and Schumm, 1979).

As an example, the data of Brice (1966, Fig. 203) were treated by the suggested method, and the results are shown on Fig. 6. The sample is small but the similarity of the slope of the shear-stress-indicator lines (- exponent rf in equation (6)) in Figs. 6 and 4 is noteworthy. Also, in both cases, valleys with small drainage areas tend to resist gullying while showing high values of the relative shear-stress-indicator (see also Fig. 5).

This study is based on the concept of geomorphic thresholds (Schumm, 1973, 1977). However, the results suggest a modified approach towards this concept. Figure 4 indicates that a threshold shear-stress-indicator may be defined, below which gully incision does not occur. However, increased values of the relative shear-stress-indicator do not imply the deterministic result that gullying indeed takes place. Rather, it implies only an increase in the probability of a valley floor to be gullied. This seems reasonable in view of the basic stochastic mechanisms involved such as the temporal and spatial distribution of rainfall, the nonhomogeneity of soil and vegetation distribution, and measurement errors. Nevertheless, the equation of the threshold line of Fig. 4 which is

$$S = .008\ A^{-.26} \tag{7}$$

defines the critical slope for drainage areas up to about 50 square miles in areas of generally similar geology, climate, vegetation and land use.

It is worthy of note also that some of the gullied valleys had slopes greatly in excess of the threshold line. This indicates that the threshold line is not fixed in position, but it can shift vertically depending on climatic fluctuations and land-use changes. For example, any activity that increases flood peaks or average discharge will cause

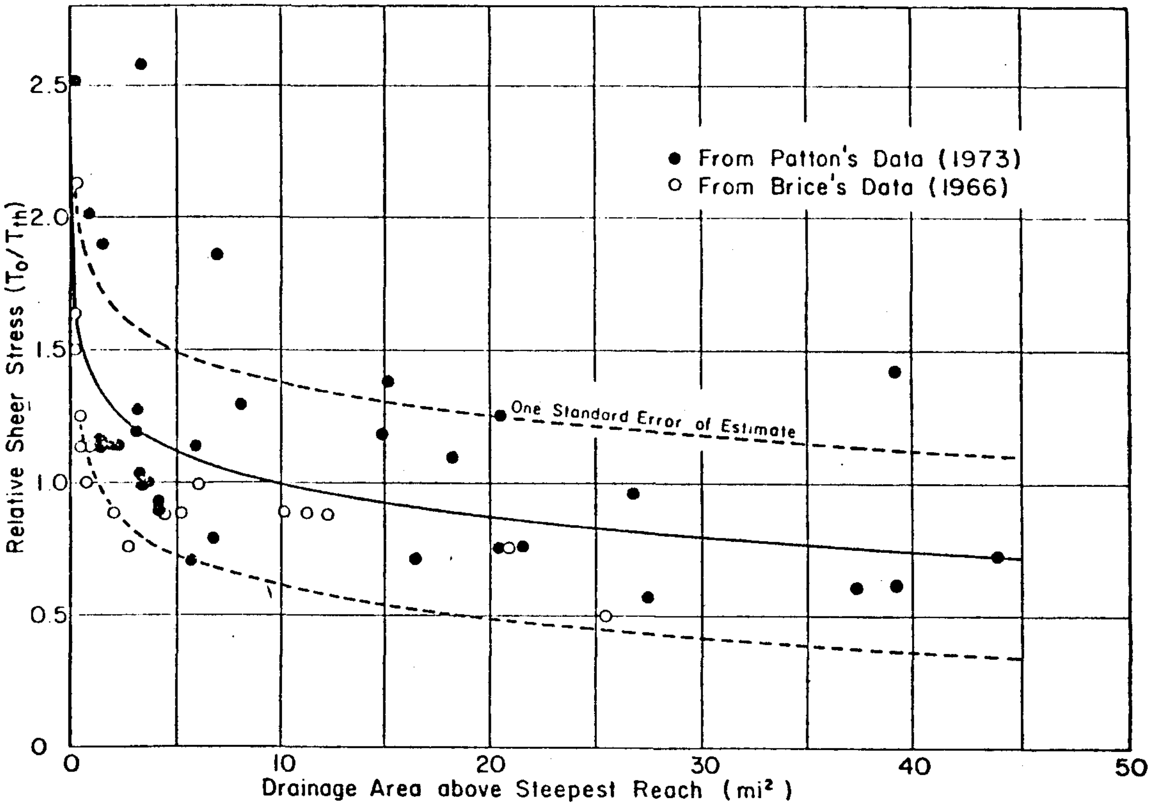

Figure 5 Relation between drainage area and Relative Shear Stress Indicator for ungullied valleys. The curve is a least-square semi-log fit; the correlation coefficient is 0.5, significant at a 0.01 level (from Begin and Schumm, 1979).

erosion of presently "stable" valley floor. The result will be a downward shift of the threshold line.

It is also important to stress that the definition of such a line (equation (7)) is only applicable to an area that is similar in all respects. For example, the Piceance Creek and Brice's threshold lines are very different (Fig. 6) reflecting different materials and climate.

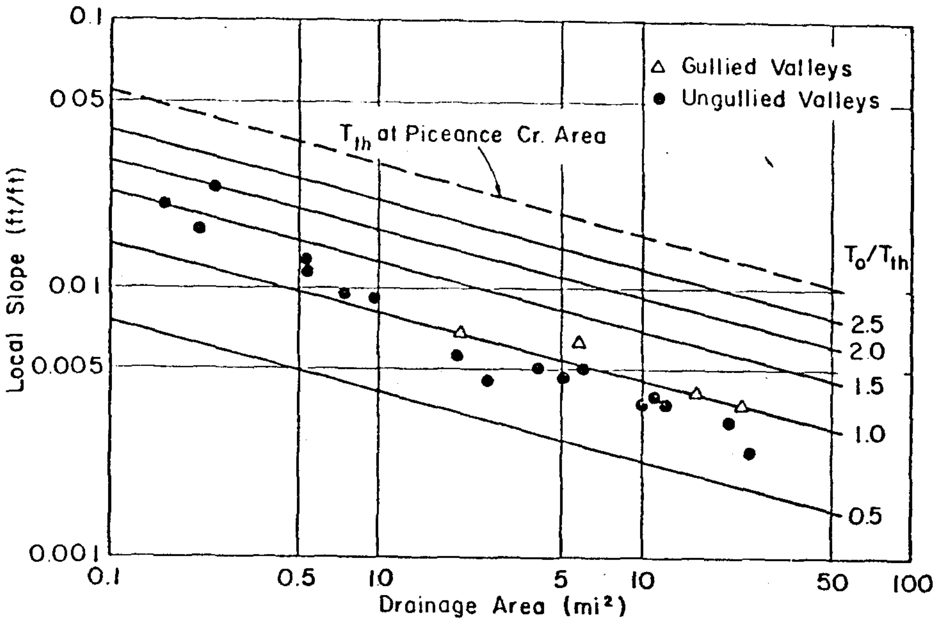

Figure 6 Drainage-area valley-slope plot showing Relative Shear Stress Indicator for Brice's Nebraska channels (from Begin and Schumm, 1979).

CHAPTER 3

STABILITY OF VALLEY FLOORS, CHALK BLUFFS AREA

In order to test the geomorphic approach to the identification of valley floor stability the Chalk Bluffs and Pine Bluffs area of northeastern Colorado were selected for further study of the threshold concept. The areal distribution of the gullies and their discontinuous character rendered them perfectly suited for research. As in the Piceance Creek area, the climate, geology, hydrology, basin morphometry, land use, vegetation, and soils vary little between basins. These variables, which would normally have to be incorporated in the analysis, were considered constants. Therefore, they do not add to the intricate nature of the problem and permit the geomorphic relationships to be more readily detected.

The discontinuous gullies in the Chalk Bluffs area are initiated on the pediment at the base of the bluffs. This is essentially a bedrock surface into which the channels have and are eroding (Fig. 7).

The situation differs from the Piceance area in that the gullies are not confined within well-define valleys. Once the drainage leaves the bluffs, the channels selected for study are within shallow bedrock depressions (valleys) on the pediment. The bedrock occasionally locally confines the flow within these shallow valleys.

General Description

The Chalk Bluffs study area is located in northeastern Colorado near the Colorado-Wyoming state line (Fig. 8). The study area is bounded by the parallels 40°45' and 41°00' North latitude and the meridians 104°45' and 104°00' West longitude. The bulk of the field area is shown on the Chalk Bluffs West, Chalk Bluffs East, Carr East, Chalk Bluffs

a

b

Figure 7 Photographs of Chalk Bluffs:
a) Discontinuous gullies in different stages of development following incision into pediment at base of Bluffs.
b) Fans at downstream ends of gullies.

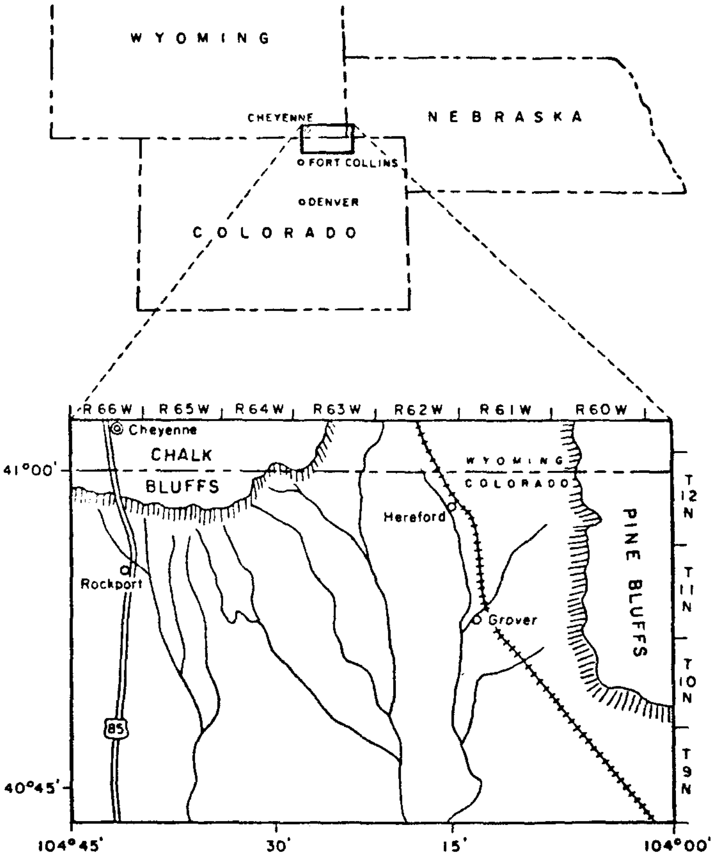

Figure 8 Location map of Chalk Bluffs study area.

Southwest and Grover Northeast 7½ minute U.S.G.S. topographic quadrangles. All of the drainage basins studied lie within a six mile wide belt below the bluffs.

The Chalk Bluffs and Pine Bluffs form the pronounced escarpment at the boundary of the High Plains Physiographic Province and its Colorado Piedmont Section (Fenneman, 1931). The Colorado Piedmont is a lowland excavated below the High Plains by the erosional activity of the South Platte River and its tributaries.

As the Colorado Piedmont was enlarged by the retreat of the bluffs, a surface composed of coalescing pediments was formed below the escarpment. The pediments were formed by the erosion of the bluffs and the removal of sediment by channelized gully erosion and unchannelized sheet flows. Unlike the typical pediments described in the literature (Rich, 1935; Hadley, 1967) these pediments lack a coarse gravel cap. This is due simply to the lack of a significant source of coarse sediment. Gully erosion is an integral part of pediment formation.

The drainage basins are characterized by flat, alluviated valley floors, gentle valley side slopes and broad interfluves.

The relief of the bluffs ranges from about 15 to 60 meters and averages 36 meters. The relief between valley floor and adjacent interfluve ranges from 3 to 20 meters. The majority of the drainage basins have their headward divides at the rim of the bluffs. Very little of the drainage area is derived from the tops of the bluffs. Drainage areas ranged from 57.3 to 0.013 square kilometers.

The gullies described are, as in the Piceance Creek area, discontinuous. Continuous gulleys exist further away from the bluffs, but they are formed by headward erosion in response to lowered base level and erosional activity of the South Platte River.

Geology - The rocks forming the Chalk and Pine Bluffs escarpments are of Tertiary age and they include the Brule Formation, of Oligocene age, which is overlain by the Ogallala Formation of late Miocene-Pliocene age (Denson, personal communication). These strata are nearly horizontal or dip very gently to the east. The unconformity between these two units is of early Miocene age, and it is represented elsewhere by the Arikaree Formation, which is present to the east of the field area (Denson and Bergendahl, 1961).

The Brule Formation consists of white, massive, blocky claystones and siltstones with occasional lenses of fine-grained sandstones. This is the unit which produces the soils and alluvium into which the gullies are eroding. The Brule Formation is composed of 77 percent silt, 12 percent clay and 11 percent very fine sand (Sato and Denson, 1967).

The Ogallala Formation is a coarse-grained sand and conglomeratic unit, which is highly resistant to erosion and it is the caprock which forms the bluffs. The Ogallala Formation is composed of 72 percent sand; 5 percent coarse, 11 percent medium, 24 percent fine and 32 percent very fine, 26 percent silt and 2 percent clay (Sato and Denson, 1967). In places, the Ogallala Formation is very coarse, containing clasts up to 46 cm in diameter.

Soils - Soil formation in the area has been restricted by small amounts of precipitation. The valley floors contain moderately thick (0.61 - 2.44 meters) alluvial deposits which exhibit poorly developed soil horizons. The upland areas have a thin residual mantle but there is negligible profile development. The soils generally reflect the character of the underlying Brule Formation with minimal alteration. The grain-size distribution reveals that these sediments can be texturally classified as a coarse silty loam. The estimated infiltration rate for these soils as estimated by the U.S. Soil Conservation Survey is from 1.5 to 5.1 cm per hour.

Climate - Mean temperature and precipitation data are available on a monthly and annual basis for two stations; Cheyenne, Wyoming which is on the High Plains surface and 19 kilometers outside the field area, and Grover, Colorado which is on the Colorado Piedmont and within the field area (Fig. 8).

The climate in northeastern Colorado is semiarid, and it is characterized by long, cold dry winters and relatively wet summers (Trewartha, 1954). The precipitation-evaporation index is about 29 (Thorntwaite, 1931). Seventy to 80 percent of the precipitation occurs in the spring and summer months when much of the precipitation occurs as heavy thunderstorms.

The elevations of the Cheyenne and Grover stations are 1868 meters and 1545 meters, respectively. The average elevations of the Chalk Bluffs and Pine Bluffs drainage basins are about 1798 meters and 1585 meters, respectively. Therefore, the climatic conditions of the study area should fall between the averages for these two stations. That is, between 33.8 and 41.3 cm of precipitation and between 44.9 and 48.1 degrees Fahrenheit (7.2 and 8.9 degrees Centigrade) temperature.

For the Cheyenne, Wyoming station, temperature ranges from an average daily high of 82.6°F (28.1°C) for July to an average low of 37.1°F (2.8°C) for January. The maximum recorded amount of precipitation in 24 hours is 2.68 inches (6.81 cm).

Vegetation and Land Use - Vegetation is of the short-grass prairie ecological group. The three dominant grass associations are gramma, western wheat and buffalo grasses (Harrington, 1954). Generally, the vegetative cover averages 40-50 percent. The presence of sagebrush is minimal, but it can be found scattered along drainage divides and on alluvial fans. Stunted Juniper and pine trees are scattered on top of the bluffs.

The area is used as rangeland for cattle. According to several land owners, settlement and grazing commenced just prior to the turn of the century, but gullies were already present. Any tendency for taller grasses and sage to grow is checked by the grazing stress upon the system. Therefore, the conditions for short grasses are always favored (Harrington, 1954). Most of the rangeland is in good to fair condition, although locally, there is evidence of overgrazing and excessive trailing by cattle. At these locations accelerated erosion is evident.

Procedure

During the summer and fall of 1977, reconnaissance, fieldwork and map measurements were conducted in the area. A total of 76 gullied or ungullied locations were scrutinized in order to study the various processes and morphologies of gully evolution. Sixty-one sites were measured along the Chalk Bluffs (50 gullied and 11 ungullied) and 15 along the Pine Bluffs (10 gullied, 5 ungullied). Forty longitudinal valley and gully profiles were surveyed in the field, these were supplemented by 36 valley floor slope measurements taken with an electronic planimeter from 1:24000, 7½ minute U.S.G.S. topographic quadrangles. Slope was measured between the closest two contours and their location was field checked at the site of gully initiation. Field measurements at all sample locations included surveying valley floor or gully cross sections and collecting sediment or soil samples. Drainage basin characteristics such as basin area, relief, gully sinuosity, basin shape, total drainage density and incised channel drainage density were also measured from 7½ minute U.S.G.S. topographic quadrangles. The percentage of vegetative cover on the valley floor was estimated for each gullied or ungullied location by taking 50 counts spaced 10 cm apart along two random orientations of a measuring tape extended 5 m along the valley floor.

Gully Initiation

In order to assess the stability or instability of a valley floor, the factors causing gully initiation must first be identified and understood. The examination of drainage basin and valley floor characteristics indicates that in the study area three major geomorphic factors influence gully initiation. These are valley floor longitudinal slope, valley floor width, and drainage basin area.

Stable or ungullied valley reaches exhibit a characteristic concave up longitudinal profile. This is similar to the classic stable, graded or equilibrium profile of perennial stream channels (Gilbert, 1877; Shulits, 1941).

However, when local deposition or sediment storage does occur, the longitudinal profile of that reach becomes convex-up (Fig. 9). The lower gradient, upstream portion of the reach of stored sediment promotes further deposition. Deposition will continue until the locally oversteepened, downstream reach exceeds a critical threshold slope and when a runoff event of sufficient magnitude triggers gully initiation (Schumm, 1977). Discontinuous gullies may form in this way at several locations along the valley profile (Figs. 2, 10).

Gully initiation is also controlled by local changes of valley floor width. A decrease of valley floor width causes runoff to become more concentrated, and therefore it increases the depth and the erosivity of the flow. It is important to note that in this area, valley floors are relatively flat, and flow events occupy the entire valley floor

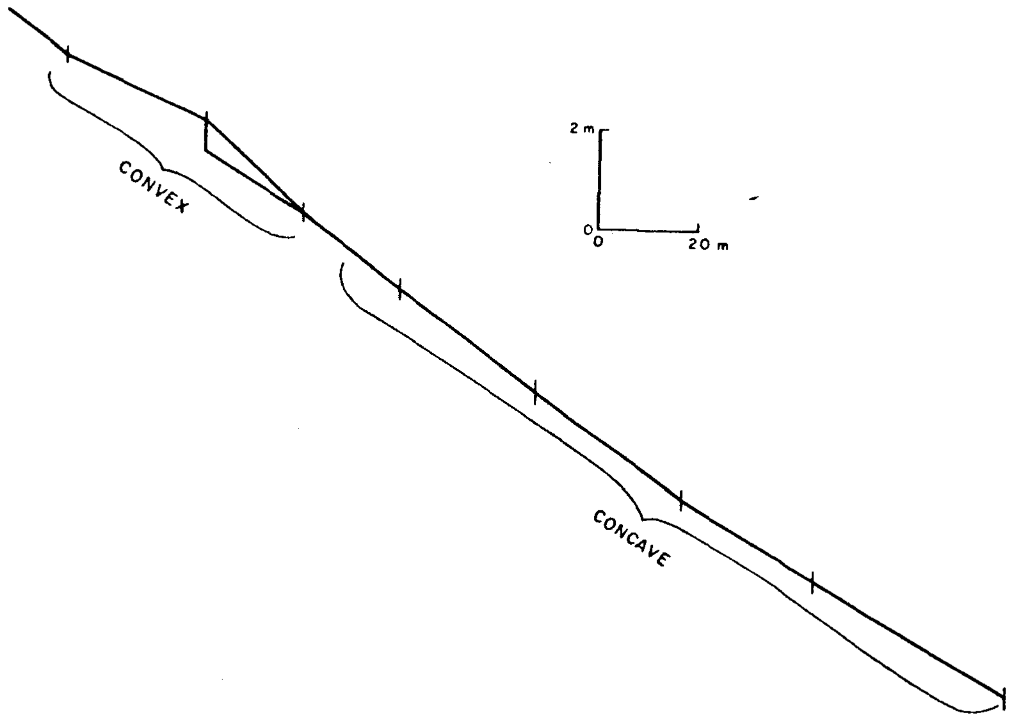

Figure 9 Longitudinal profile showing both concave and convex sections of valley . Note discontinuous gully developed in convexity.

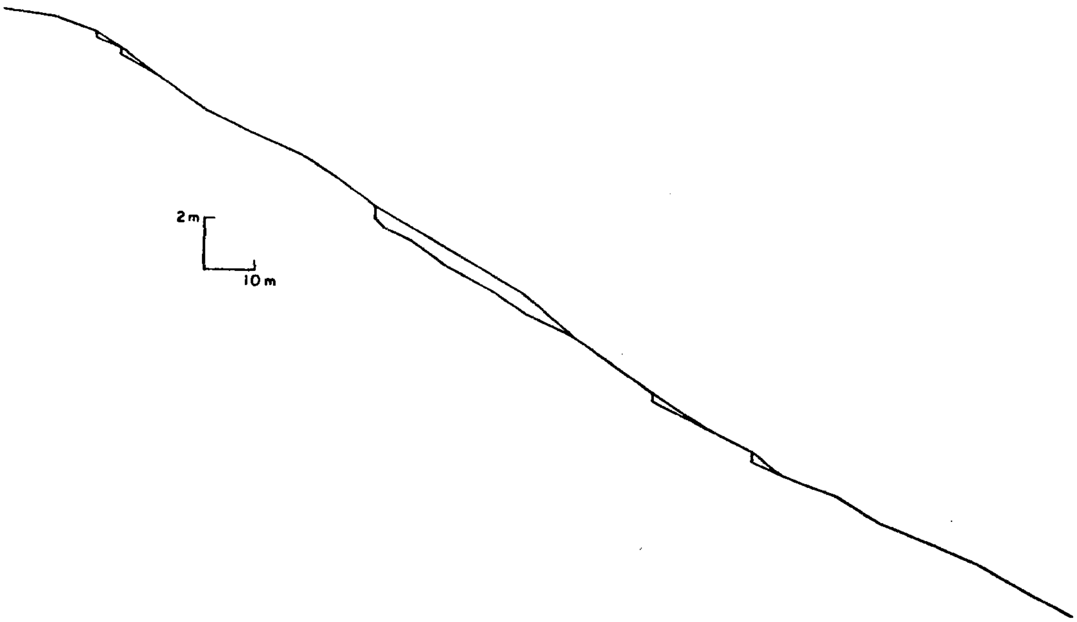

Figure 10 Longitudinal profile of valley showing multiple convexities and gullies.

width. Therefore, a gully is initiated upon, and it usually occupies the entire valley floor. In other gullied regions, the valley floor may not be as uniform and flow may only occupy a portion of the floor. Therefore, in this situation, valley floor width can be used for flow width.

Valley floor width does not change whereas valley slope changes in response to erosional and depositional processes. However, valley floor width can affect valley floor slope stability because a decrease in width increases flow velocity and erosional forces. Therefore, a combination of steep valley floor slope and narrow valley floor width create a favorable condition for fully initiation. On Fig. 11 valley floor transverse and longitudinal profiles illustrate the combined effects of decreased flow width and increased slope upon gully initiation.

The third factor influencing gully initiation is the amount of runoff or discharge delivered from the drainage basin. Although local changes in valley floor width and slope create conditions favorable for gully initiation, a storm event with a sufficient amount of runoff energy is required for erosion. The stochastic nature of runoff events in terms of frequency and magnitude, and the hydrologic complexities of the rainfall/runoff relationship introduce an indeterminant or probabilistic nature to the gully problem. Nevertheless, it has been demonstrated statistically that drainage-basin area is the best estimator of discharge (Burkham, 1966). Thus, drainage-basin area is the third geomorphic factor influencing gully initiation.

The valley reaches which display an increase of valley floor slope are referred to as critical locations (Heede, 1960).

Although there are a few gullies which clearly owe their origin to overgrazing, critical locations would be the sites most affected by such

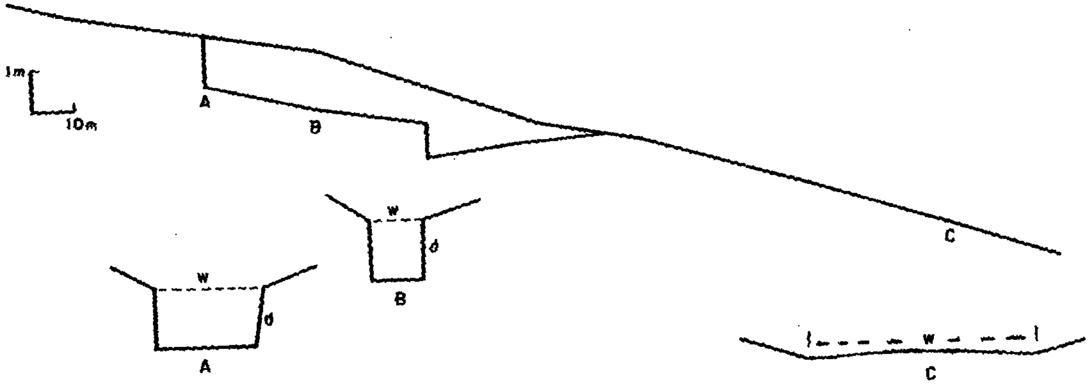

Figure 11 Longitudinal profile of valley and cross sections showing effect of valley floor slope and width on gully location.

activity. Lusby et al. (1971) stated that grazing generally increases runoff because cattle trample and decrease the infiltration capacity of loose soil. Also, excessive trampling and grazing tend to remove or at least diminish the effect vegetative cover has on reducing rainfall energy, runoff and erosion. An analysis of variance was performed to determine if there was greater variation of vegetative cover within a drainage basin than between drainage basins. The variation of vegetative cover within each sampled group of gullied or ungullied critical locations was greater than the vegetative cover variation between the two groups. Therefore, except for obvious instances of trampling and trailing, the effects of grazing upon gully initiation may be considered constant among the areas studied.

Valley Floor Stability

Although in the Chalk Bluffs area variations in climate, geology, vegetation, sediment, and land use are relatively minor; nevertheless, as Fig. 12 shows, a threshold slope cannot be clearly identified. The line drawn on Fig. 12 lies above most of the ungullied locations, but gullied locations plot below it. However, as noted above, the valleys are different and at some locations the width of the valley is constricted by bedrock. In addition, the majority of the sampled valleys are within drainage basins smaller than the 4-7 square mile size that produced equivocal results in the Piceance basin study.

The procedure developed for the Piceance Creek area was modified to permit evaluation of the effects of valley width, and a ratio of valley slope for valley width is plotted against drainage area on Fig. 13.

The relation of Fig. 13 is less clear than that of Fig. 2 or 3 but nevertheless, it is possible to draw two threshold lines on Fig. 13. Above the upper line there are no ungullied locations, and below the

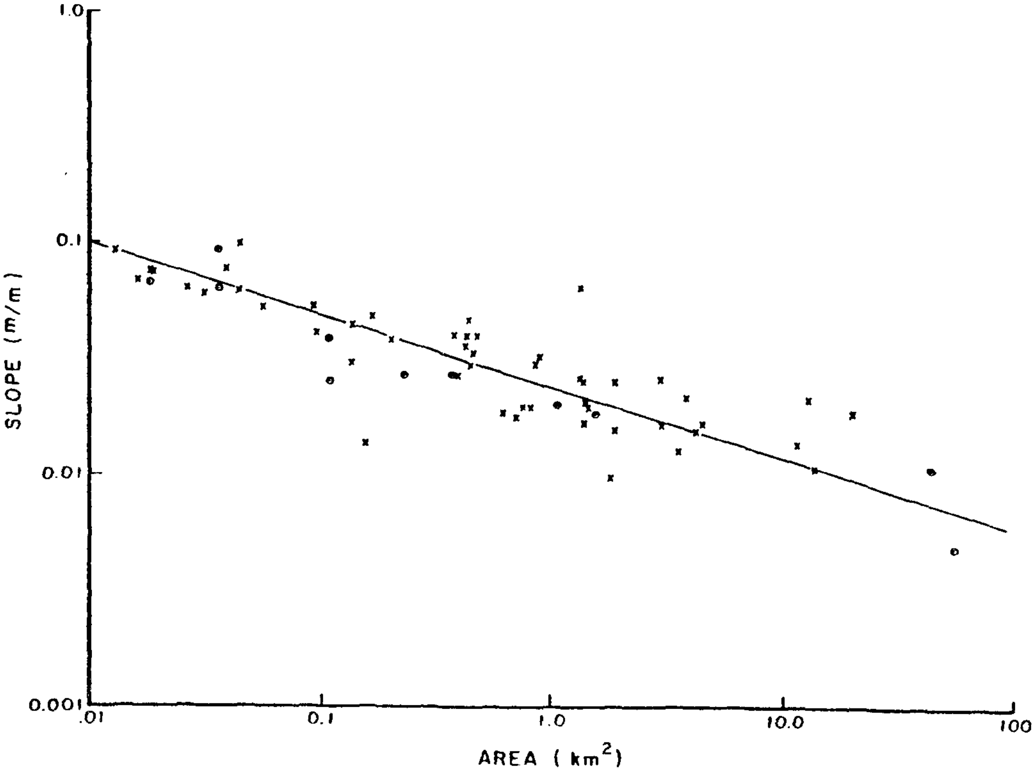

Figure 12 Plot of drainage area and critical valley slope,
Chalk Bluffs area. x = gullied, o = ungullied valleys.

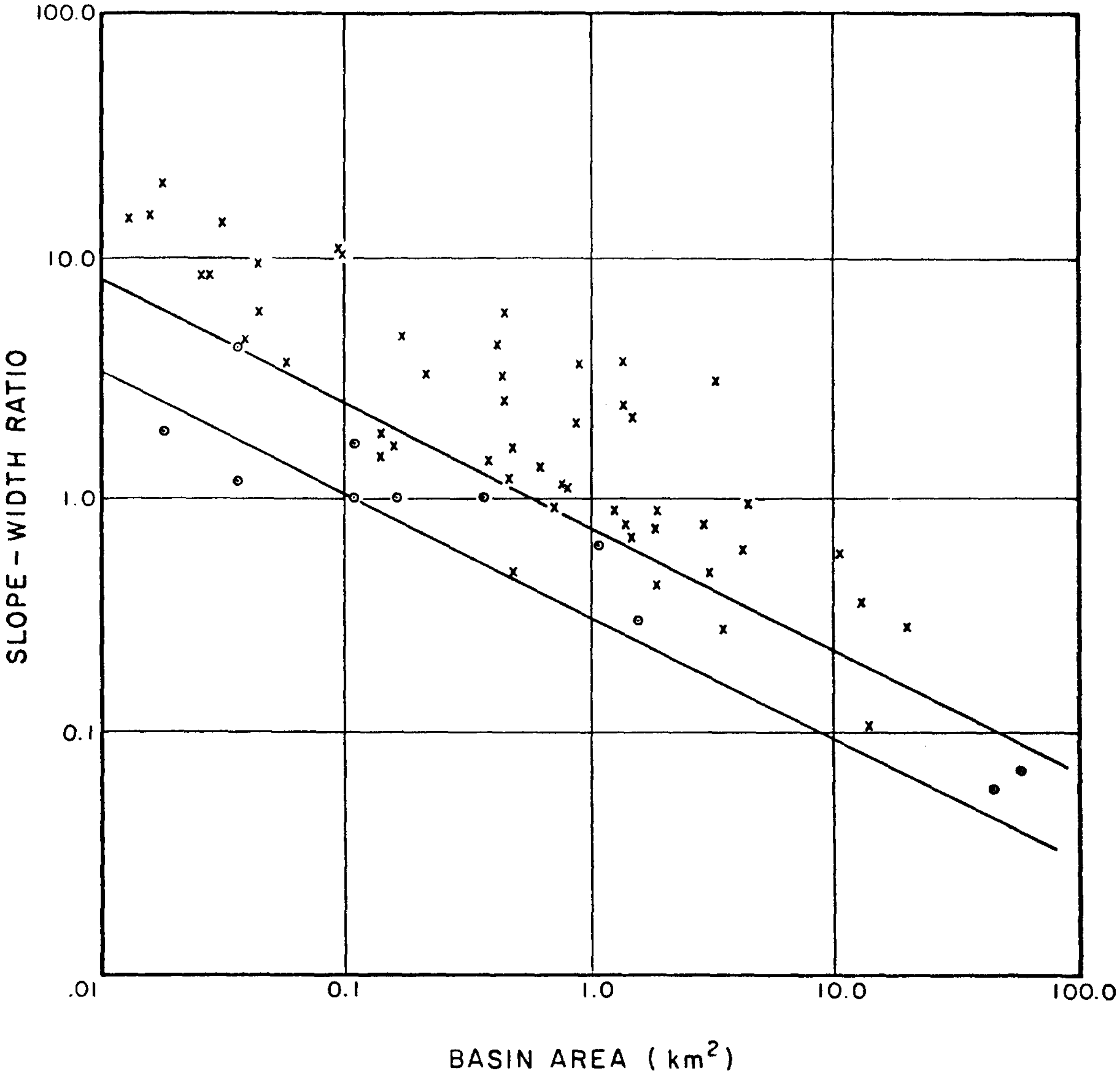

Figure 13 Plot of valley-slope - width ratio against drainage area. Note threshold zone separating stable (o) from gullied (x) valleys.

lower line there are no gullied locations. A threshold zone has been identified based on the slope-width ratio and drainage area. Only three ungullied locations plot below the zone, but many additional ungullied reaches of low S/W ratio could have been found to fill in this field on Fig. 13. Again the very high values of S/W for many of the gullied locations suggest that the threshold line or zone has been shifted downward, perhaps as a result of the drought years of the 1930's or because of increased grazing pressure.

Figure 13 supports the concept of a threshold valley slope for the Chalk Bluffs area, and it indicates that many of the presently stable or ungullied locations are susceptible to erosion.

The shear-stress index of valley stability, as used earlier, must be modified because of the addition of valley width or flow width. In the Chalk Bluffs area a stream power index can be used (Fig. 14). The physical significance of stream power is well-known (Simons and Richardson, 1966; Bagnold, 1966). Bagnold (1966) defined stream power as "the rate of work performed by the transporting fluid or the rate of energy loss per unit length of stream."

The development of a relationship between stream power and geomorphic and hydraulic variables begins with the well-known equation for shear stress:

$$\tau_o = \gamma RS, \tag{8}$$

where τ_o is the shear stress at the water-channel interface, γ is the weight per unit volume of the water and considered a constant, R is the hydraulic radius of the flow, and S is the valley slope which is an approximation of the energy slope. Stream power is simply shear stress (τ_o) multiplied by velocity (V):

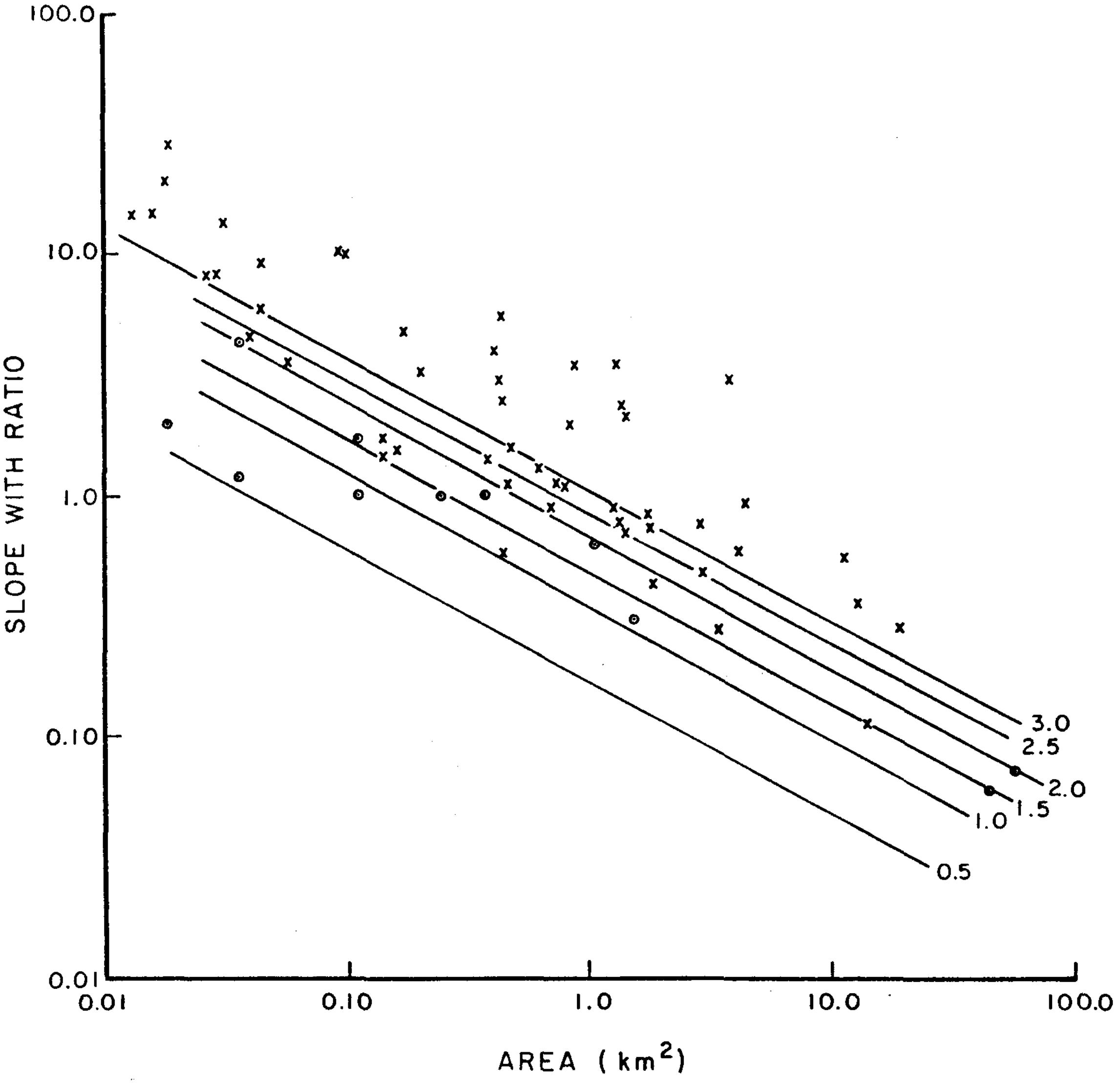

Figure 14 Plot of valley-slope-width ratio against drainage area. Lines show constant values of Relative Stream Power, Chalk Bluffs area.

$$\tau_o V = \gamma RSV \tag{9}$$

Hydraulic radius (R) is the ratio of cross-sectional area (Ac) to wetted perimeter (P):

$$R = Ac/P \tag{10}$$

Substituting equation (10) into equation (9) yields:

$$\tau_o V = \gamma \frac{Ac}{P} SV \tag{11}$$

Cross-sectional area (Ac) is related to discharge (Q) and velocity (V) by the continuity equation:

$$Q = Ac\ V$$

or

$$Ac = Q/V \tag{12}$$

Substituting equation (12) into equation (11) yields:

$$\tau_o V = \gamma \frac{Q}{V} \frac{S}{P} V \tag{13}$$

or

$$\tau_o V = \gamma Q \frac{S}{P} \tag{14}$$

Wetted perimeter (P) is best estimated by the valley floor width (W). This is based on the assumption that the flow event occupies the entire valley floor. Discharge (Q) is best estimated by drainage basin area (Ab) (Burkham, 1966). Therefore:

$$\tau_o V = K\ A_b \frac{S}{W} \tag{15}$$

where K is some constant.

The advantage of defining the geomorphic threshold in terms of stream power instead of a simple critical slope/critical width ratio is that it allows consideration of all three variables of gully initiation, namely valley floor slope, valley floor width and drainage area.

There are two means by which the stream power geomorphic threshold can be exceeded and gully erosion initiated. This is achieved by either an increase of discharge or by an increase of valley floor slope. Normally channel width does not change, but artificial construction of flow will effectively decrease the width and it will probably cause incision.

In most cases, the width of the valley floor is well-defined, but for some sample locations near the base of the bluffs the valley floor or flow path was difficult to identify. In order to test if the data was biased for these samples, because gully top width was taken as the valley floor width, discriminant function analysis was also performed on only the well-defined valley floor gullied and ungullied samples. The analysis resulted in a comparable F statistic of 17.59, also significant at the .01 level, which indicates no bias exists.

The distance a sample plots from the threshold line is related to the degree of stability or instability in terms of the critical stream power ($\tau_o V_{th}$). The stream power value ($\tau_o V_o$) of each location can then be compared to the critical stream power ($\tau_o V_{th}$) as a ratio:

$$\tau_o V_{rel} = \frac{\tau_o V_o}{\tau_o V_{th}} \tag{13}$$

to yield a value of relative stream power ($\tau_o V_{rel}$). Thus, a quantitative means for comparing each critical location's degree of stability is established. Lines of equal relative stream power ($\tau_o V_{rel}$) were calculated and plotted as lines parallel to the threshold stream power ($\tau_o V_{th}$) line in Fig. 14.

The equation of the lower line of the threshold zone is:

$$S/W = 0.35\ A^{.55}$$

and hence for any locations the critical slope-width ratio can be calculated.

Summary

The recognition and quantification of the variables that identify the erosional geomorphic threshold at which gullies are initiated provides a means for predicting the stability of alluvial valley floors. The effects of land use and other external factors appear to be minimal in the study area. Therefore, gully initiation is controlled by the intrinsic character of the valley floor which is reflected by changes in valley floor longitudinal slope and valley floor width. These changes result in the development of a convexity on the valley floor which is the site of gully initiation. The critical values of valley floor width and slope are dependent upon the drainage area or discharge above the critical location.

It is important to note that this approach is a purely deterministic one, but the stochastic behavior of rainstorm events which trigger gullying requires a probabilistic approach. The occurrence of intense rainfall covering relatively small areas is a distinctive feature of thunderstorm precipitation in the western United States (Leopold, 1942). Also, higher intensity thunderstorm systems are generally more limited in areal distribution. Figure 15 illustrates the change of alluvial valley floor stability as the geomorphic threshold zone is approached. Superimposed on the line of increasing valley instability (Line 1) are vertical lines which represent precipitation events of varying magnitudes and frequencies. As time progresses, the valley slope width ratio $(\frac{S}{W})$ increases and the degree of valley instability approaches the geomorphic threshold. High magnitude, low frequency storm events have little

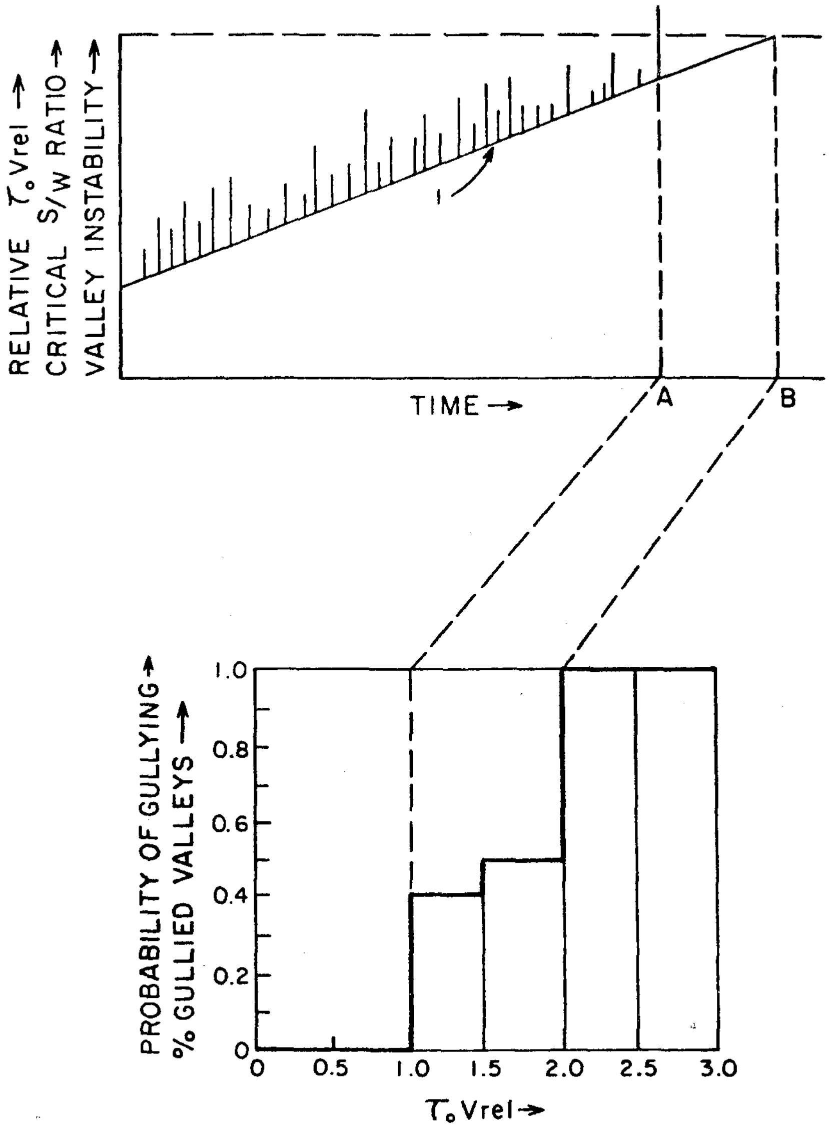

Figure 15 Change of valley - floor stability with time, as related to the probability of gullying for increased values of Relative Stream Power. See text for discussion of these relationships.

effect on gully initiation until increased valley instability permits failure at (Time A). Although failure occurred at Time A, lower-magnitude, higher-frequency events would have initiated gullying at Time B in any case. Therefore, a zone of increasing probability for an erosional event exists between Time A and Time B. This zone is represented in the stream power model (Fig. 14) by the area between the relative stream power values of 1.0 and 2.0. On Fig. 15, the percentage of gullied critical locations in each relative stream power ($\tau_o V_{rel}$) increment illustrates how the probability of gullying increases, as relative stream power increases. This probability plot can be a useful tool for determining priority locations for conservation measures (Begin and Schumm, 1978). Therefore, any gullied locations that plot below or within the threshold zone, such as the two gullies in the 1.0 and 1.5 relative stream power zone, do not necessarily owe their origin to external factors such as overgrazing. Instead, an extremely high-magnitude storm event may be the initiator as shown on Fig. 15.

The critical locations which are ungullied but which plot in the threshold zone are interpreted as potentially unstable (Fig. 13). Therefore, these locations demand a high priority for gully prevention treatments. Conservation measures should concentrate on either reducing the discharge at the critical location or modifying the critical slope and/or critical width of the critical location. In other words, the conservation measures should be designed to reduce relative stream power.

The stream power model can also be used to evaluate the planned effects of land use within a drainage basin. For example, if the effects of grazing, surface mining or urbanization upon the rainfall-runoff relationship is quantified, the resultant discharge increase, in terms of basin area, can be located along the abscissa of the stream power model (Fig. 13). Thus, the effect of increased discharge upon the stability of a valley reach can be ascertained and incorporated into the land-use plan.

CHAPTER 4

CONCLUSIONS

If critical slope-area plots or critical slope-width-area plots can be developed for an area of similar climate, geology, land use, etc., then as based on the results of investigations in the Piceance Creek and Chalk Bluffs areas, it should be possible to identify threshold zones that enable identification of incipiently unstable valley floors. The prediction of the sites of discontinuous gully development should be possible for this area.

Although the critical shear stress and stream power concepts provide an understanding of the forces involved, nevertheless a graphical approach is simpler and clearly identifies the critical slope or slope-width values (Figs. 3, 13).

Additional studies indicate the problem that can be encountered during an attempt to develop relations like those presented on Figs. 3 and 15. A study of gully solution and distribution west of Trinidad, Colorado failed to produce a figure similar to Figs. 3 and 13. In this area coal mining, recreation activities and grazing has not reduced the threshold value that threshold zone cannot be identified because even the gentlest valley floor is incised when flow is concentrated in roads and trails (Chamberlin, 1979).

In the Burger Creek area between Gillette and Buffalo, Wyoming, gullying was initiated by a shift or change of level of the Powder River. The rejuvenation of tributary forms to Burger Creek is controlled more by the position of Burger Creek in its valley than the morphology of the tributary valleys (Parsons, 1979, written communication).

Hence, it is likely that the threshold approach will not be successful in many areas because the threshold conditions have been greatly altered or other factors overwhelm the effects of valley slope and width.

The threshold conditions are not fixed and any land use, hydrologic, or climatic alteration can change the stability conditions. If the changes affect the entire area the threshold line may shift downward, which will render additional valley floors unstable.

When the change is local, it may have the effect of shifting a plotted point to the right, thereby bringing it closer to or crossing the threshold line. Theoretically there should be no points that plot a considerable distance above the threshold line, but in fact, on both Figs. 2 and 15 numerous locations have a very high ratio of shear stress to critical shear stress or stream power to critical stream power. This apparently indicates that the threshold has shifted downward. Increased agricultural activity and the drought year of the 1930's plus extreme storm events could have caused this downward shift of the threshold line.

The obvious deduction is that within any area erosional activity will be variable and at least the smaller components of the landscape need not be in the same stage of erosional or depositional development. For the most part this is exactly the case encountered in semiarid regions of western United States. However, the relations developed for the Piceance Creek and Chalk Bluff areas indicate that the distribution of erosional features can be explained, and therefore additional erosion may be predictable.

REFERENCES

Bagnold, R. A., 1966, An approach to the sediment transport problem from general physicism: U.S. Geological Survey, Prof. Paper 422I.

Begin, Z. B. and Schumm, S. A., 1978, Instability of alluvial-valley floor-A method for its assessment: American Soc. Agr. Engineering, Vol. 22, pp. 347-350.

Bradley, M. T., 1980, Gully development and valley stability, northeastern Colorado: Unpublished M.S. Thesis, Colorado State University, in preparation.

Brice, J. C., 1966, Erosion and deposition in the loess-mantled Great Plains Medicine Creek drainage basins: Nebraska U.S. Geological Survey, Prof. Paper 352-H.

Burkham, D. E., 1966, Hydrology of Cornfield wash area and the effects of land treatment processes: 1951-1960: U.S. Geological Survey, Water Supply Paper 1831, 87 p.

Chamberlin, D. C., 1979, Gulley erosion in submontane basins near Trinidad, Colorado: Unpublished M.S. Thesis, Colorado State University, 82 p.

Denson, N. M. and Bergendahl, M. H., 1961, Middle and upper tertiary rocks of southeastern Wyoming and adjacent areas: U.S. Geological Survey, Prof. Paper 424-C.

Fenneman, N. M., 1931, Physiography of the western United States, McGraw-Hill, New York, 534 p.

Gilbert, G. K., 1877, Report on the geology of the Henry Mountains: Dept. of the Interior, Washington, D.C., 160 p.

Grafi, W. L., 1979, The development of montane arroyos and gullies: Earth Surface Processor, Vol. 4, pp. 1-14.

Hadley, R. F., 1967, Pediments and pediment-forming processes: Jour. Geol. Education, Vol. 15, pp. 83-89.

Harrington, S. D., 1954, Manual of plants of Colorado: Sage Books, Denver, 666 p.

Heede, B. H., 1966, Stages of development of gullies in western United States: Zeit, Geomorph., Vol. 18, pp. 260-271.

Leopold, L. B., 1942, Areal extent of intense rainfalls: American Geophys. Union, Trans., Vol. 23, pp. 558-566.

Leopold, L. B., Wolman, M. G., and Miller, J. P., 1964, Fluvial processes in geomorphology: Freeman, San Francisco, 522 p.

Lusby, G. C. et al., 1971, Effect of grazing on the hydrology and biology of the Badger wash basin in western Colorado, 1953-1966: U.S. Geological Survey Water Supply Paper 1532-D, 90 p.

Partheniades, E. and Paasewell, R. E., 1970, Erodibility of channels with cohesive boundaries, American Soc. Civil Engineers, Hydraulic Div. Jour., Vol. 96, pp. 755-771.

Patton, P. C., 1973, Gully erosion in the semiarid west: Unpublished M.S. Thesis, Colorado State University, 129 p.

Patton, P.C. and Schumm, S. A., 1975, Gully erosion, northwestern Colorado: A threshold phenomenon, Geology, Vol. 3, pp. 88-90.

Rich, J. L., 1935, Origin and evolution of rockfans and pediments: Geol. Soc. America, Bullir, Vol. 46, pp. 999-1024.

Sato, Y. and Denson, N. M., 1967, Volcanism and tectonism as reflected by distribution of non-opaque heavy minerals in some tertiary rocks of Wyoming and adjacent states: U.S. Geological Survey, Prof. Paper 575-C, pp. 42-54.

Schumm, S. A., 1973, Geomorphic thresholds and the complex response of drainage systems, in: Morisawa, M. (ed): Fluvial geomorphology, Publ. in Geomorphology, SUNY, Binghamton, N. Y., pp. 299-310.

Schumm, S. A. and Hadley, R. F., 1957, Arroyos and the semiarid cycle of erosion: American Jour. Science, Vol. 255, pp. 161-174.

Shulits, S., 1941, Rational equation of river-bed profile: Amer. Geophys. Union, Trans., Vol. 22, pp. 622-630.

Simons, D. B. and Richardson, E. V., 1966, Resistance to flow in alluvial channels: U.S. Geological Survey, Prof. Paper 422-J.

Thornthwaite, C. W., 1931, The climates of North America according to a new classification: Geogr. Review, Vol. 21, pp. 633-655.

Trewartha, C. T., 1954, An introduction to climte: McGraw-Hill, N. Y., 402 p.